National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

All-weather tropospheric
3D Wind
from microwave sounders

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3D wind from space: State of the art

AMV: GOES and similar geostationary satellites

- Method: Track cloud and water vapor features
- Observations used: Brightness temperatures => ~ T(feature)
- Height registration: Forecast T(z) => ~ z(feature)
- Pros: Very frequent obs. (5-15 min); covers large portion of a hemisphere
- Cons: Uncertain height registration; limited coverage

AMV: MODIS

- Method: Similar to GOES
- Coverage: Polar regions only
- Pros: Polar-region coverage complements GOES
- Cons: Uncertain height registration; infrequent obs. (≤ 100 min); limited coverage

CMV: MISR

- Uses parallax motion from multi-angle cameras during 7-minute overflight interval
- Pros: Precise height registration
- Cons: Cloud top winds only; limited dynamic range; sparse global coverage

All cloud methods: Poor coverage in mid-troposphere due to few clouds there

Doppler lidar: Coming (soon?)

- Pros: Very high vertical resolution; precise height registration
- Cons: Obscured by clouds; sparse coverage; limited laser life time

Alternative: Atmospheric sounders

AMV: Track water vapor features

- Method: Track water vapor features (similar to GOES and MODIS)
- Observations used: Retrieved q(z,t) – no need for forecast input
- Height registration: Absolute (referenced to $p_{surface}$)
- Pros: Accurate height registration; uniform coverage throughout troposphere
- Cons: Moderate spatial resolution (~ 2 km vertically, 5-25 km horizontally)

Infrared sounders (current)

- Example: AIRS (Aqua), CrIS (S-NPP)
- Coverage: Polar regions only (similar to MODIS)
- Cons: Infrequent obs. (≤ 100 min); limited coverage; obscured by clouds

Microwave sounders (current)

- Example: AMSU (NOAA), ATMS (S-NPP) – Coming soon: CubeSat MW sounders
- Coverage: Polar regions only (similar to MODIS)
- Pros: Penetrates clouds
- Cons: Coarse spatial resolution

Challenge: Temporal sampling

- All are polar-orbiting LEO satellites => polar coverage only, long sampling intervals
- Requirement: Sampling interval ~5-20 minutes
- Solution: Small-sat (LEO) cluster; Large-sat (GEO) single sensor ← Best solution!

Best option: GEO

GEO sensors achieve high temporal resolution: minutes
- Important for observations of highly dynamic processes and phenomena
- Ideal for wind measurements through feature tracking
- Ideal for monitoring of high-intensity short-duration precipitation events

GEO sensors provide continuous coverage: minutes→days→weeks
- Important for observation of storm life cycles
- Important for rain totals (storms or regions)

IR sounders: Clouds are problematic
- Need to do "hole hunting" or limit to above-clouds
- Can't get observations in or below clouds

Best: MW sounders
- Meteorologically "interesting" scenes: Full cloud cover; Severe storms & hurricanes
- Cloud liquid water distribution
- Precipitation & convection
- Above all: Can observe water vapor features through clouds → Wind everywhere

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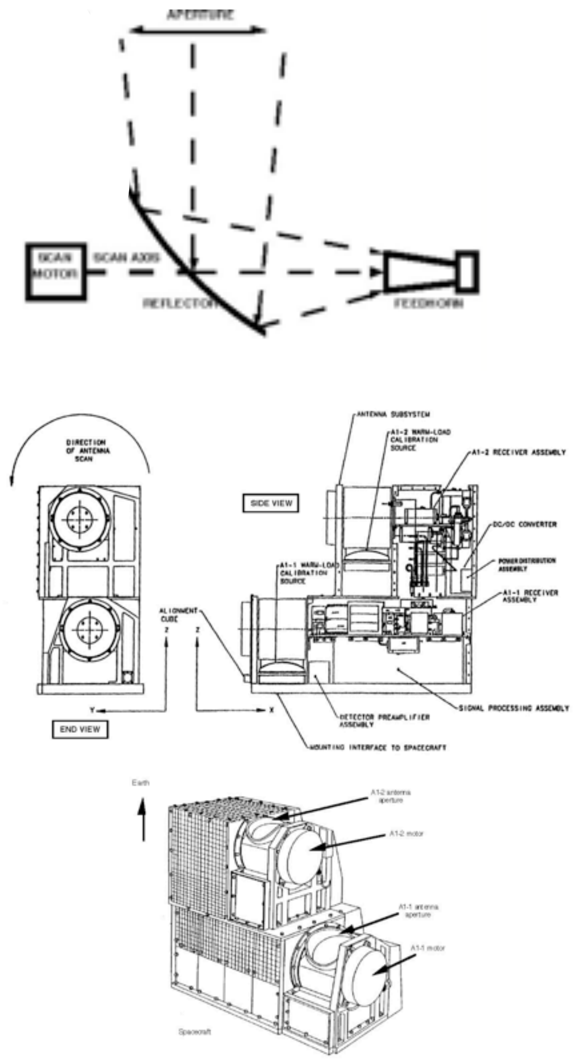
So why don’t we already have GEO/MW?

Pre-Decisional Information -- For Planning and Discussion Purposes Only



Low-earth-orbiting MW sounder (AMSU)

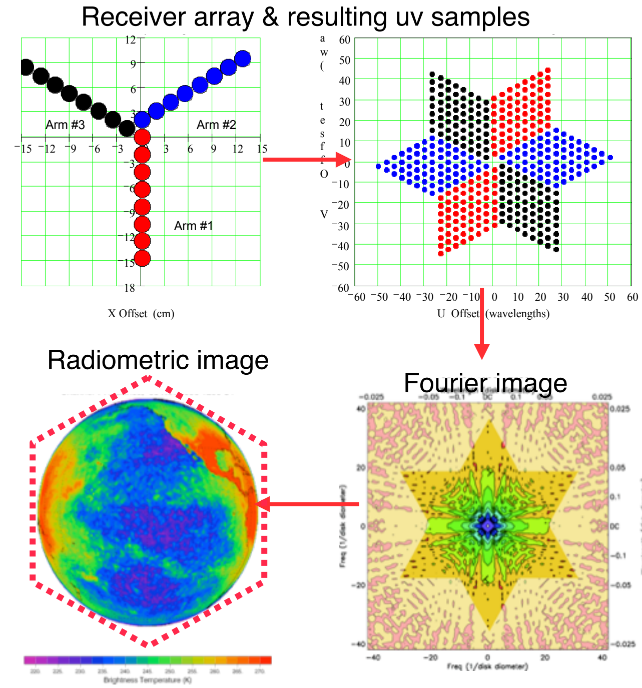
The antenna is the key, and the problem…

- **Antenna size is determined by distance and “spatial resolution”**
- **AMSU antenna is 15 cm dia. ⇒ 50-km resolution from 850 km**
- **GEO orbit is ~36000 km ≈ 42 x 850 km**
- **AMSU-antenna must then be 42 x 15 cm to give 50-km res. from GEO**
- **This is 6.5 meters! Not feasible!**
  This can be reduced somewhat by degrading the antenna efficiency - but still impractical
- **Solution: *Synthesize* large antenna ⇒ GeoSTAR**

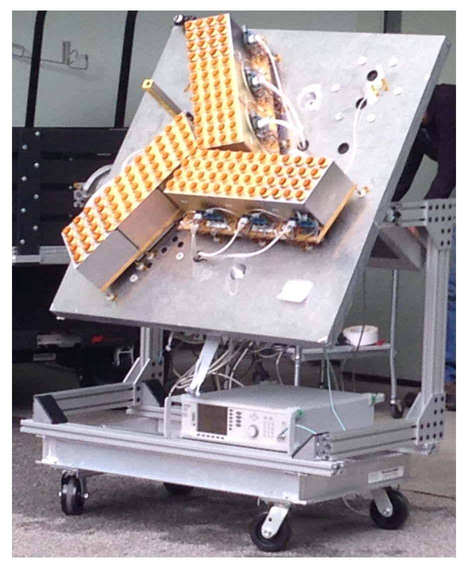
Solution: GeoSTAR

- **Aperture-synthesis concept**
  - Sparse array employed to synthesize large aperture
  - Cross-correlations -> Fourier transform of Tb field
  - Inverse Fourier transform on ground -> Tb field
- **Array**
  - Optimal Y-configuration: 3 sticks; N elements
  - Each element is one I/Q receiver, 3.5λ wide (2.1 cm @ 50 GHz; 6 mm @ 183 GHz!)
  - Example: N = 100 ⇒ Pixel = 0.09° ⇒ 50 km at nadir (nominal)
  - One “Y” per band, interleaved
- **Other subsystems**
  - A/D converter; Radiometric power measurements
  - Cross-correlator - massively parallel multipliers
  - On-board phase calibration
  - Controller: accumulator -> low D/L bandwidth

This is the only viable “array spectrometer” design and is what the NRC had in mind



Proof-of-concept prototype developed at JPL

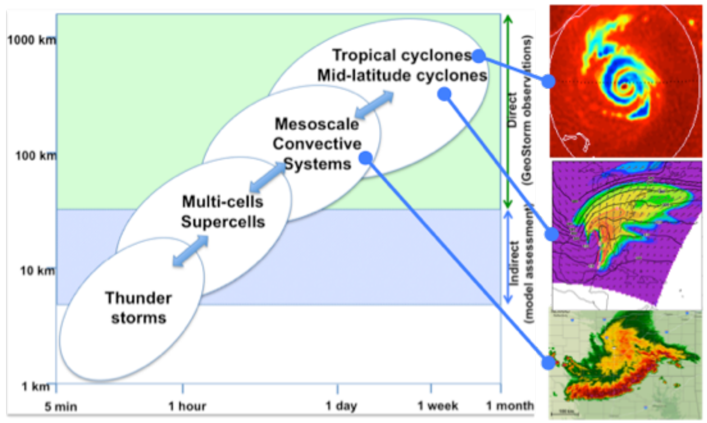


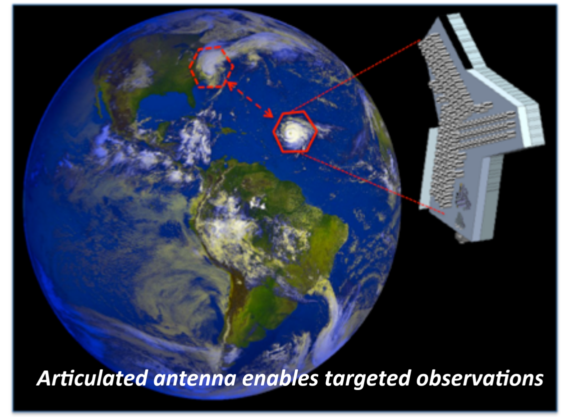
"GeoStorm": A GEO/MW mission concept

A GEOSTATIONARY MICROWAVE SOUNDER MISSION FOCUSED ON THE EVOLUTION OF SEVERE STORMS

Improve our understanding of sudden and unpredicted change in intensification and motion of destructive storms:

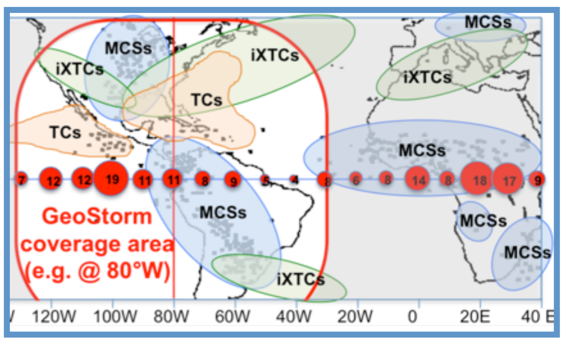
- ***hurricanes***
- ***severe thunderstorms and mesoscale convective systems***
- ***mid-latitude cyclones and winter storms***





Low cost as a hosted payload

Many hosting opportunities in GEO:



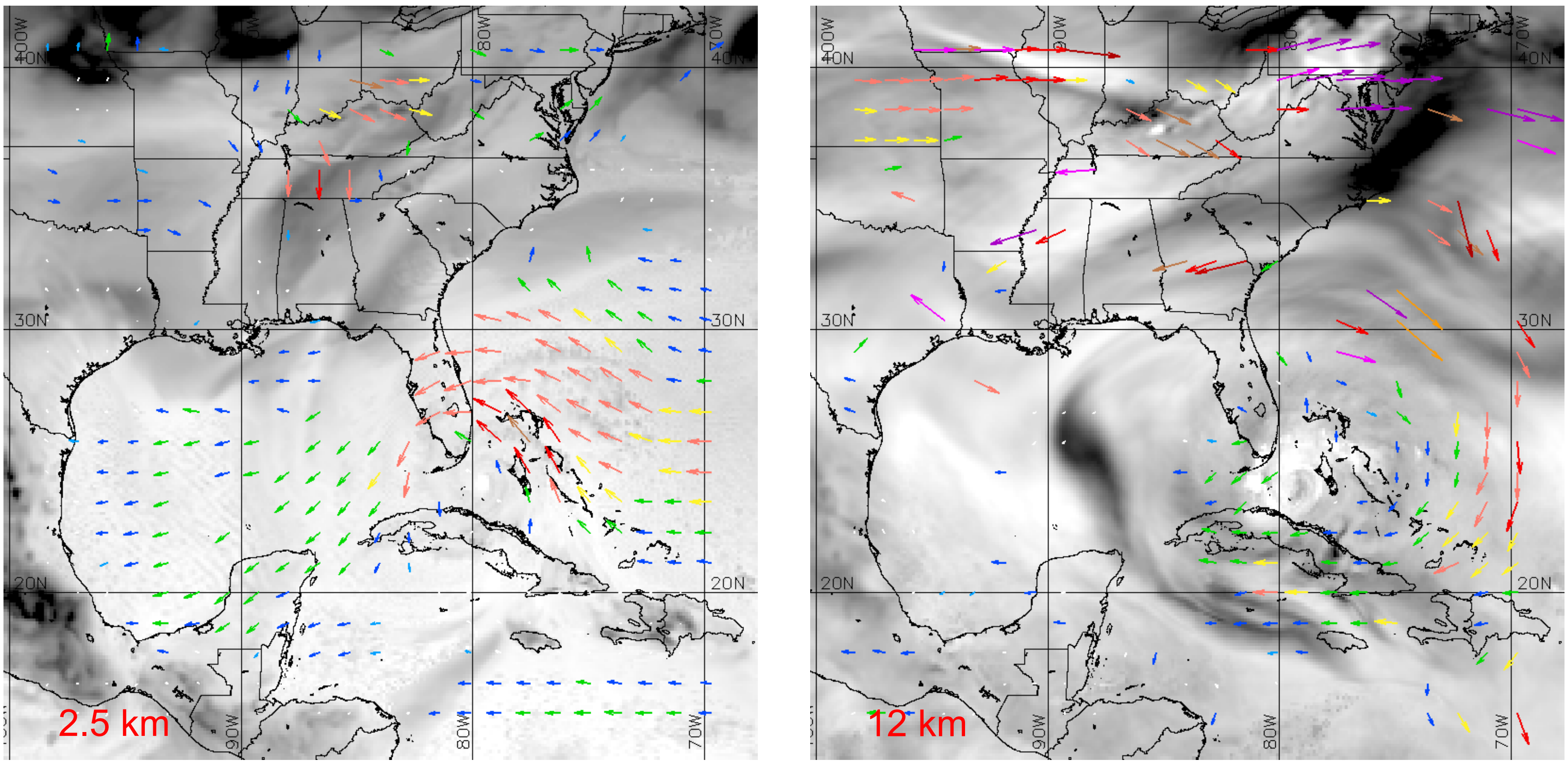
There are more than 80 GEO comm-sats that provides a view of the Americas, being replaced at a rate of 5-6 per year

GeoStorm Highlights	
Targeted observations	Life cycle storm tracking
Time-continuous	Capture dynamic processes; diurnal cycle fully resolved
Multiple simultaneous key parameters	Temperature, humidity, precipitation, wind
All-weather	Cloud/rain-penetrating
3-D observations	1000 km dia x 15 km vert. (volume); 25 km dia x 3 km vert. (resolution)
Wide coverage	All storms visible from GEO

This mission concept was used as the basis for an OSSE study of 3D wind capabilities

Example

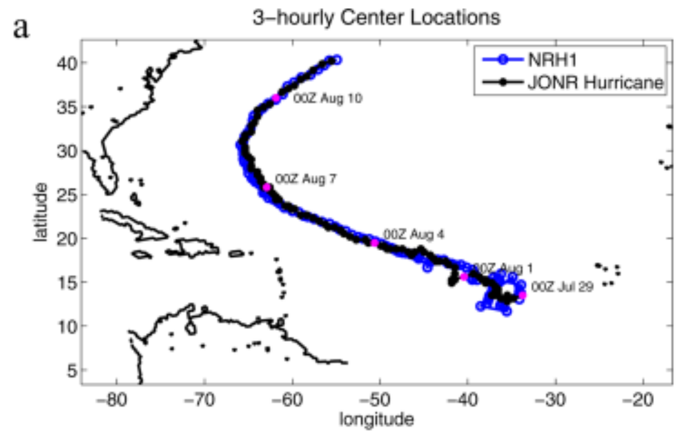
WRF simulation of Rita (2005)



Credit: S. Hristova-Veleva & J. Turk, JPL

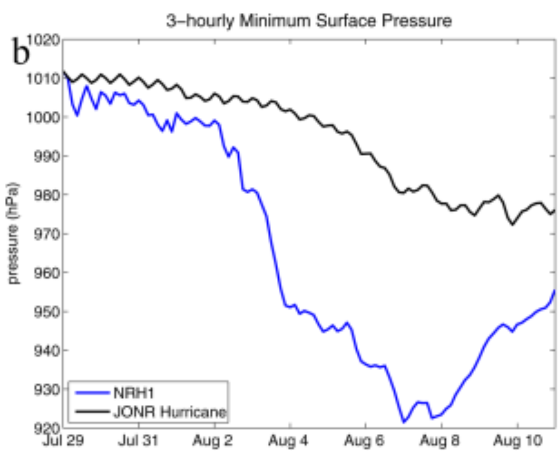
Wind OSSE: Nature run

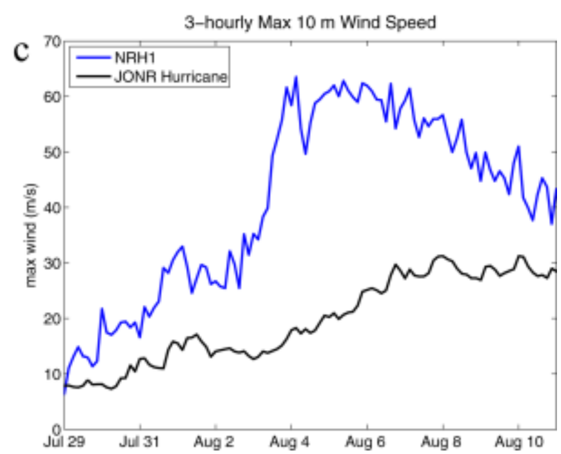
WRF simulation embedded in global model; developed by NOAA
Simulates NATL hurricane for 13 days



Four nested grids:
1. **27 km 30 minutes (240x160)**
2. **9 km 30 minutes (120x120)**
3. **3 km 30 minutes (240x240)**
4. **1 km 6 minutes (480x480)**

The 3 innermost grids follow the storm





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http://onlinelibrary.wiley.com/doi/10.1002/jame.20031/full#jame20031-fig-0004

GeoStorm simulations

Simulated q(x,y,z,t) derived from nature run fields

- Replicate GeoStorm spatial resolution
- Replicate GeoStorm temporal sampling
- Replicate GeoStorm precision
- Used primarily Grid 4 (1 km, 6 minutes)

Horizontal spatial

- Convolve NR with 25-km gaussian ⇔ 25-km horizontal resolution

Vertical resolution

- Convolve NR with AMSU-like averaging kernels ⇔ 2-3 km vertical resolution

Temporal

- Convolve NR with 15-minute box-car averaging kernel ⇔ 15-minute averaging

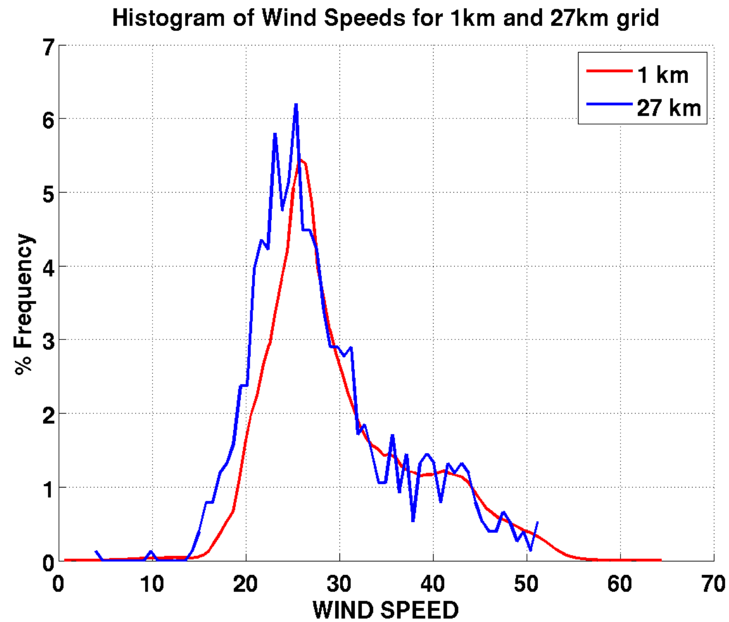
Noise

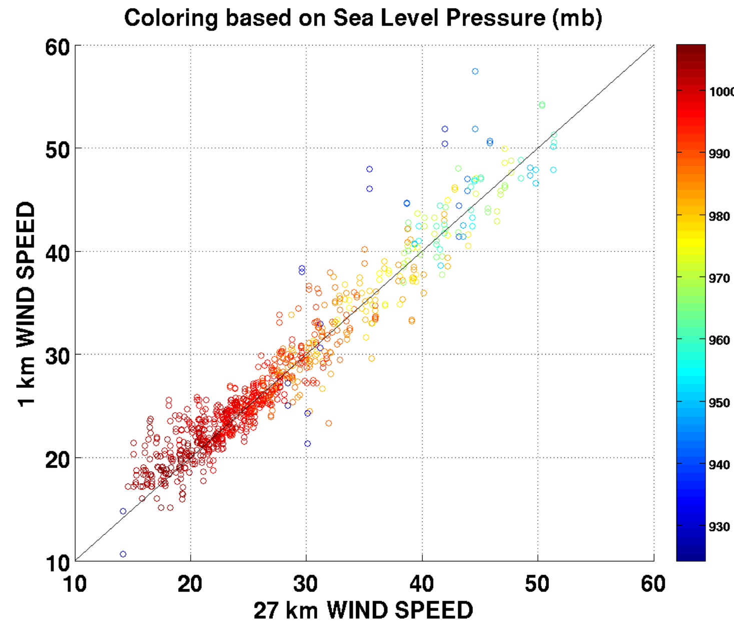
- Add ~25% random noise to convolved q

Precipitation filtering according to MIRS retrieval capabilities

- Rain rate < 1 mm/hr: All cases accepted
- Rain rate > 1 mm/hr and < 3 mm/hr: Only above 700 mb accepted
- Rain rate > 3 mm/hr: All cases rejected

Some NR wind statistics





NR wind speed distribution for Grid 1 (blue) and Grid 4 (red)

Shows that model wind does not strongly depend on spatial scale

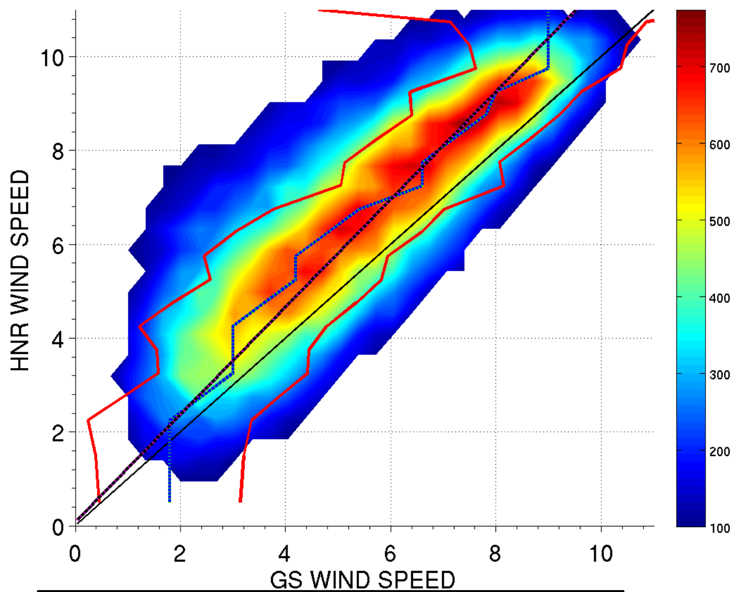
NR wind speed vertical distribution for Grid 1 (horizontal axis) and Grid 4 (vertical axis)

Shows that vertical distribution of wind also does not strongly depend on spatial scale

GeoStorm simulation results

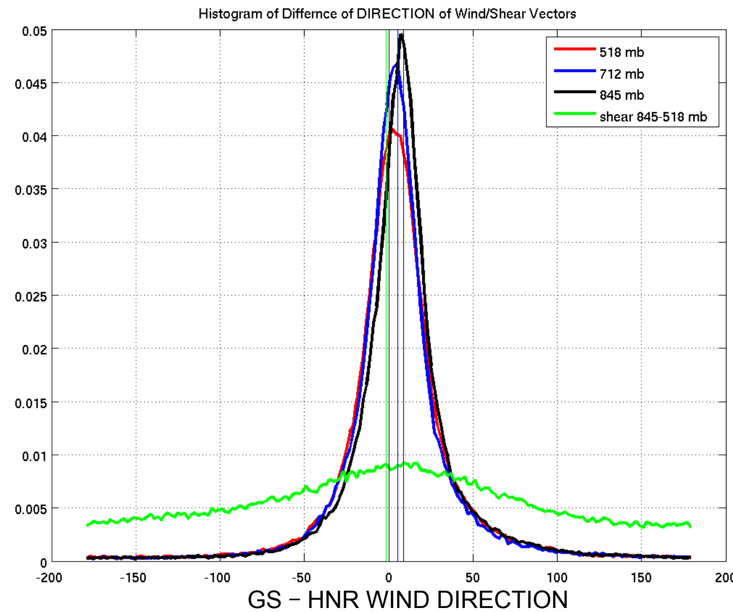
Based on large sample size (> 5000); cases with rain rate < 1 mm/hr

Wind speed: Histogram @ 845 mb



Red lines indicate 1-sigma levels
Black line: Best fit, nearly linear
Precision (rms) = 1.7 m/s; bias = -1 m/s

Wind direction: 3 pressure levels



Direction at 3 pressure levels
Also showing wind shear
Precision (rms) < 15°; bias < 6°

Summary:
Precision < ± 2 m/s - This meets WMO requirements for wind

Pressure level (mb)	Bias		RMS error	
518	-0.8 m/s	2°	1.9 m/s	14°
712	-1.2 m/s	3°	1.6 m/s	11°
845	-1.0 m/s	6°	1.7 m/s	10°

The LEO option: Additional simulations

How to achieve adequate temporal sampling from LEO

- Frequent overpasses: Polar regions (polar-orbiting satellites)
- Multiple satellites: E.g., 2xMODIS, nxAMSU
- Cluster of small-sats

Nominal architecture

- 3 CubeSats flying in formation, 5-15 minutes apart
- Each has a MW sounder (e.g., MASC)
  - Minimum capability: water vapor sounding, T also desirable

Nature run

- WRF simulations of pre-hurricane tropical atmosphere, 1 hour
- 4-km grid
- 5-minute intervals ⇔ 11 samples in 1 hour

Simulations

- Convolve with AMSU averaging kernels ⇔ 2-3 km vertical resolution
- NR temporal & horizontal sampling ⇔ 4 km horizontal resolution. 5-minutes
- Precipitation filtering: < 1 mm/hr only
- Noise: Same as for GEO case

LEO constellation simulation results

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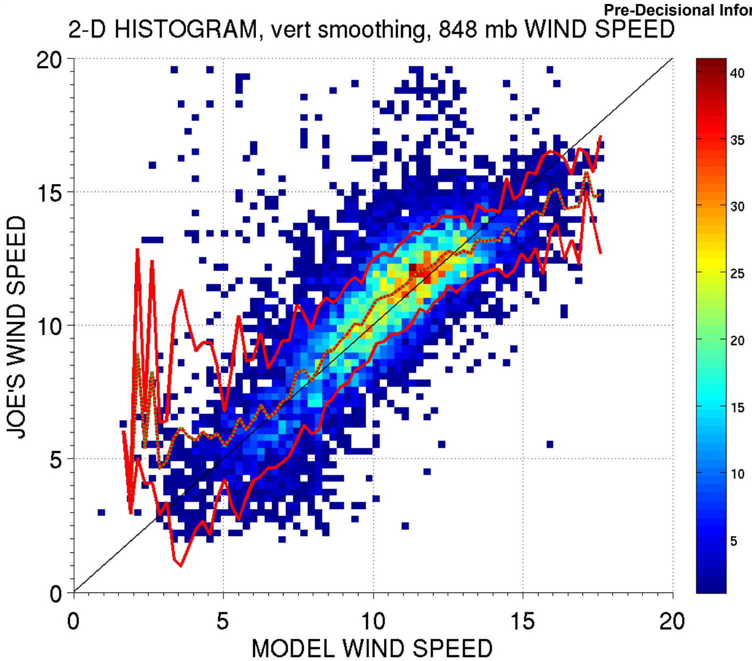

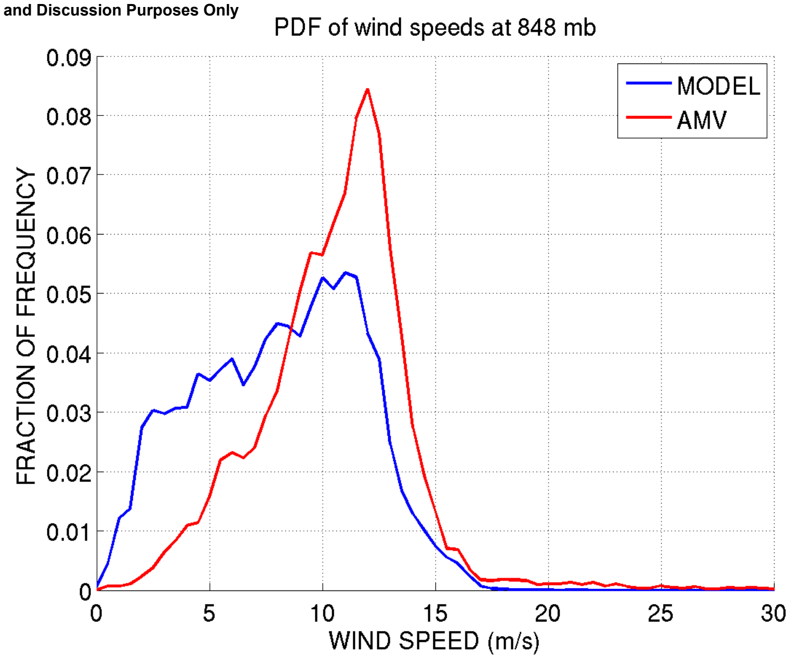

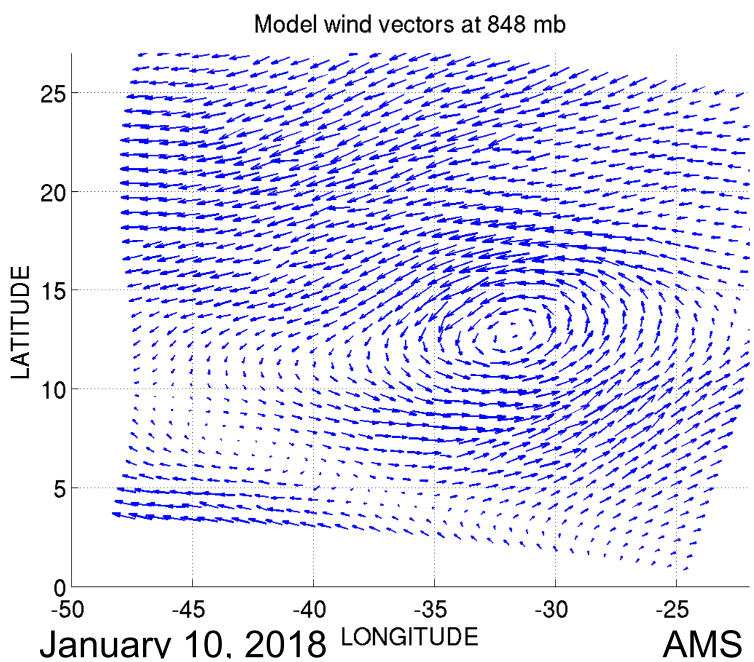

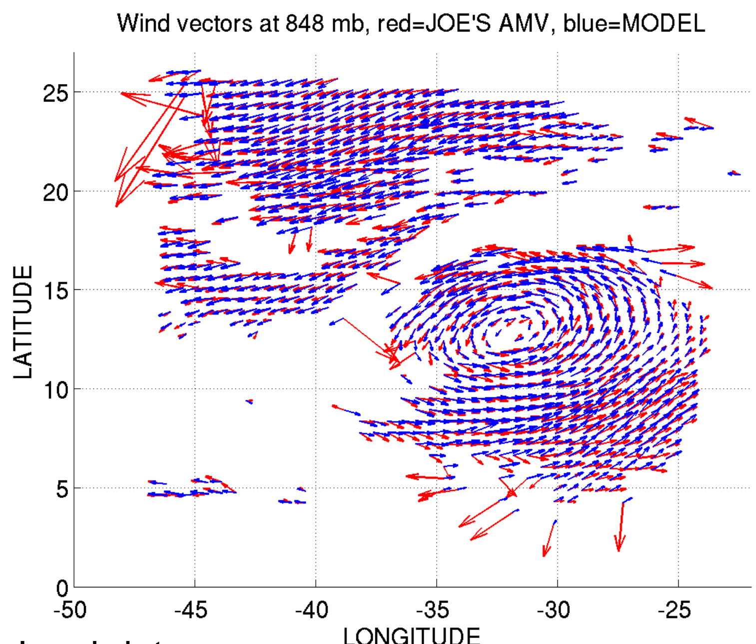

Summary

- Both simulations yield < ±2 m/s precision, low bias
  - GEO simulations have robust statistics
  - LEO simulations based on small sample
  - Accuracy & precision are not sensitive to instrument noise
    - Due to spatial averaging by AMV algorithm (32x32 box pattern detector)
    - To be investigated further
- Rain is only a minor factor
  - MW sounders are not affected by clouds
  - Even tropical cyclones exceed 3 mm/hr in relatively small areas
  - Advanced retrieval systems can account for rain
    - System developed at JPL (Schreier, *personal comm*) works at ~ 10 mm/hr
- Future work
  - Determine dynamic range & precision vs. Δt and $\Delta x,\Delta y$
  - See if AMV algorithms can be improved
  - Apply resolution enhancement to GEO case → 5-10 km, 5 min
    - Algorithms developed at JPL (Yanovsky, *JSTAR, Rem.Sens.Lett.*)

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